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TITLE: Soft X-Ray Spectral Measurements For Temperature Determination of Laser Produced Aluminum Plasmas

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SOFT X-RAY SPECTRAL MEASUREMENTS FOR TEMPERATURE DETERMINATION OF LASER PRODUCED ALUMINUM PLASMAS

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Abstract

Time and space resolved measurements were made on plasmas produced by the SPRITE laser focused on aluminum targets. The experimental spectra are compared to theory in order to determine a characteristic plasma temperature.

Summary

Time and space resolved spectral measurements were made on aluminum plasmas produced by the SPRITE laser focused on aluminum targets. The laser irradiance was 1000 J/cm^2, and the pulse duration 60 nanoseconds. Radiation from the plasma was focused on the slit of a grating spectrometer by a toroidal mirror on an axis normal to the laser beam and parallel to the target surface. The spectrometer was coupled with a time gated microchannel plate detector giving a time resolution of 30 nanoseconds. These data were recorded as a video signal and processed by an IBM AT computer.

These spectra are unique and exhibit both space and time-dependent features that extend 15 mm from the target and radiate for at least 50 nanoseconds after the laser is off. Ionization states of Al IV and Al V are seen in the spectra, characteristic of a 10 eV plasma temperature. The afterglow is remarkably intense showing cooling characteristics and recombination.

Theoretical line emission spectra are calculated over a range of densities and temperatures. These results are used to determine the "state" of the plasma as a function of space and time. The calculated spectra are based on a data bank of multiplet energy levels and transition probabilities computed using R. D. Cowan's atomic structure code. State populations are predicted using the assumption of local thermodynamic equilibrium.

Introduction

We report the results of time and space resolved spectroscopy experiments on plasmas produced by a 0.25-μm single-pulsed laser focused to 3-mm diam spot on flat aluminum targets. The laser irradiance was 10^3 J/cm^2 in a pulse whose full width was 60 ns. These experiments were conducted at SPRITE, a KrF laser facility, at the Rutherford-Appleton Laboratory in England. They were a joint US/UK effort during June and July 1986 that was sponsored by the SDI laser vulnerability and lethality program.

The broad objective of this work is to provide physical measurements of the plasma temperature and density as verification of modeling calculations. LASNEX was used to model a plasma produced by laser at 0.25 μm focused on aluminum targets.[1,2] For a laser irradiance of 10^3 J/cm in a single pulse of 60 ns the calculated temperature was 15 eV and the density of the order of 10^{20}/cm^3.

We have observed spectra from laser-produced plasmas for a range of laser irradiances on target in two separate previous experiments. We show a typical spectrum, from an aluminum target, in Fig. 1.

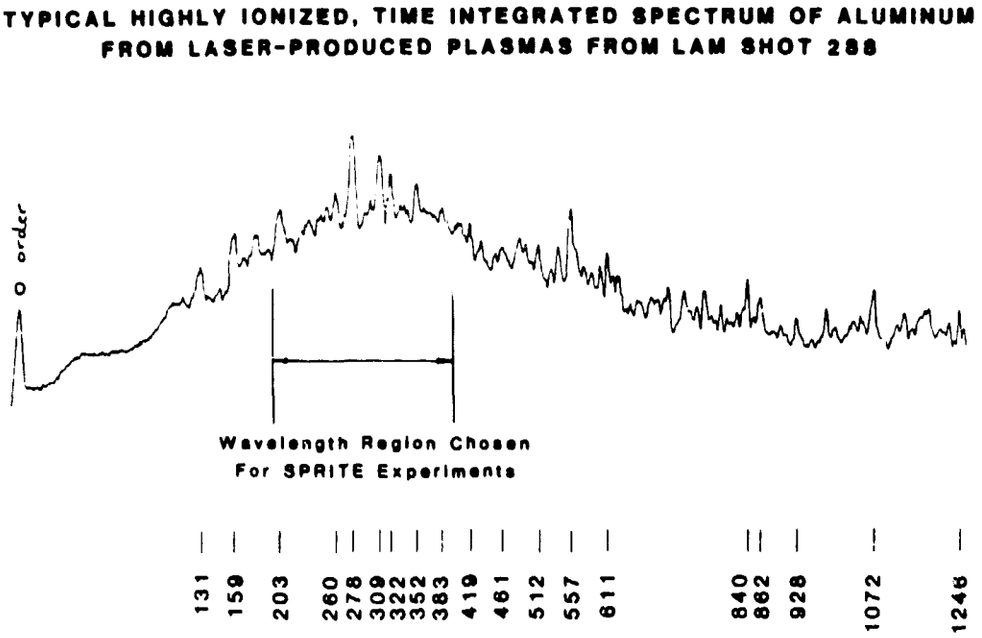

Figure 1. Wavelength selection for SPRITE experiments.

This spectrum was recorded on film from a grazing irradiance spectrograph and is qualitive in nature. Note, however, the spectrum reaches a peak at about 300 Å and exhibits considerable line structure. For an optically thin plasma, with a temperature of 15 eV, ground state lines of Al IV through Al VII should be observed in emission in the wavelength region from 130 Å to 400 Å. Our experiment was to measure the time and spatial dependence of the emission of these lines in a limited wavelength region from 190 Å to 400 Å.

Experimental Arrangement

In the SPRITE experiment we coupled SPRED, a vacuum ultraviolet/soft x-ray spectrometer, to the target chamber in a manner shown in Fig. 2. We observed radiation from the plasma

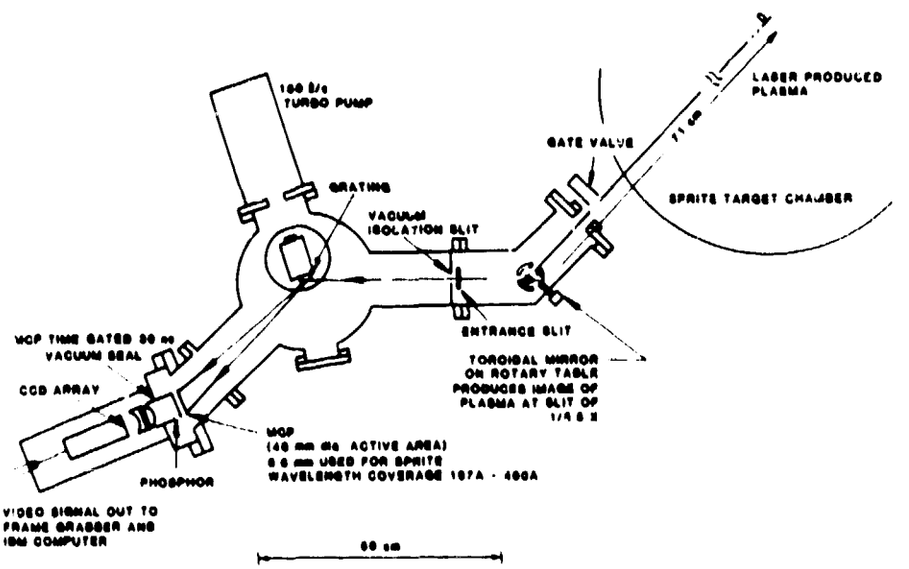

Figure 2. Spectrometer configuration for SPRITE experiments.

transverse to the laser beam. This radiation was focused by a toroidal mirror and produced a demagnified image (1:1/5.5) on the slit of the spectrometer. The grating was also a toroidal figure with 455 g/mm used at an angle of incidence of 70°. The grating focused a point on the entrance slit to a point at the image plane. The two-dimensional image (wavelength vs space) was recorded with a microchannel plate (MCP) detector. This MCP detector had a gold stripline which we gated with a high voltage pulse, of 30 ns in duration, to obtain time resolution.[3] The visible image at the phosphor screen was focused 1:1 by a f/0.85 lens onto a CCD camera. Subsequently, this image was processed as a video signal by a frame-grabber as a single event and stored on hard disc in an IBM AT computer.

The CCD camera had 491 pixels in 6.6 mm in the wavelength direction, 382 pixels in 8.8 mm in the spatial direction and had an 8-bit (256) gray scale.

The wavelength coverage was from 190 Å-400 Å with a dispersion of 0.46 Å/pixel. The actual resolution was 1.5 Å or 3 pixels.

The field of view was 28 mm normal to the target surface. One pixel is 23 microns at the slit or 126 microns at the source. The point spread function for the toroidal mirror was ~40 microns that resulted in the actual spatial resolution at the source to be 270 microns or 3 pixels.

Results

Time resolution was attained from a sequence of shots where the gate time was held at 30 ns and was advanced in time with respect to the laser pulse. An example of raw data is shown in Fig. 3. Here we have a sequence of four shots timed from the onset of the laser pulse, t_o. The laser pulse was 60 ns at full width. Each of the shots covered the identical wavelength and space dimensions. The wavelength coverage is from 197 Å to 400 Å and spatial dimension is from the target surface to 13 mm. The target was 6061 aluminum. Spectrum A in the sequence is from 5-35 ns, B is from 30-60 ns, C is from 55 to 85 ns, and D is from 80 to 110 ns, all relative to t_o. We note that during intervals A and B the laser pulse was on and during intervals C and D the laser was off. We will label C and D as afterglow spectra. It is apparent from these spectra that these emissions are highly time and space dependent. Excited material is expanding away from the target surface and is emitting rich line spectra. Two general observations: the emission from the plasma is considerably greater during the afterglow than during the laser pulse and, the duration of the afterglow is at least 50 ns after the end of the laser pulse. For comparison we include a time-integrated spectrum which should be a composite of the time resolved spectra shown.

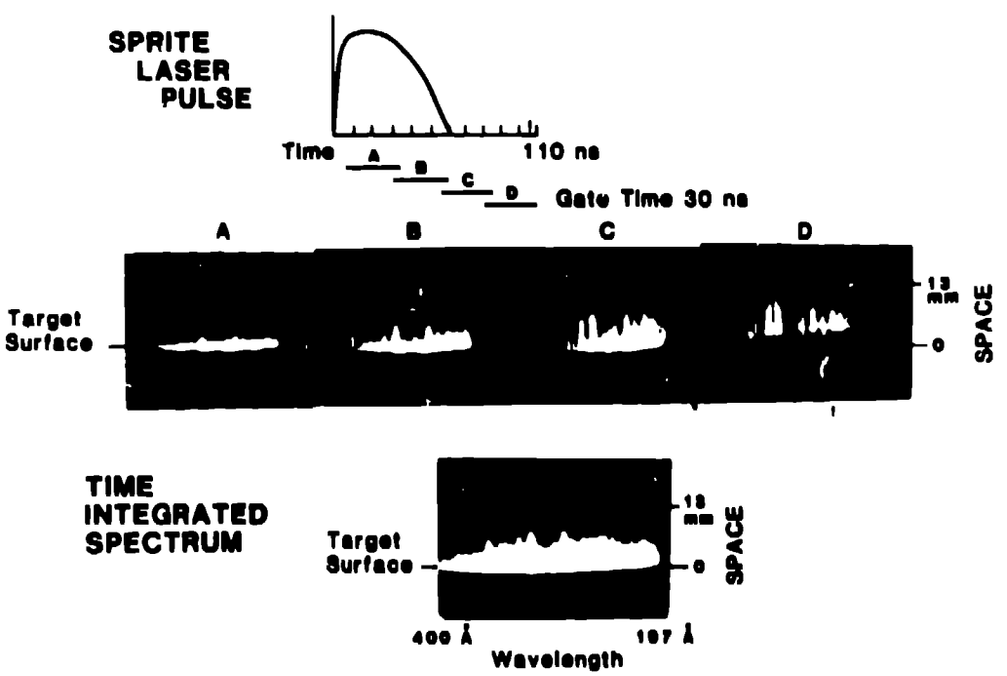

Figure 3. Time-space resolved spectra from Al targets at 1000 J/cm².

In Fig. 4 we show spectral scans from 210 Å to to 375 Å in a matrix of time and space of the plasma. These data are plotted for four shots with times after t_o of 5-35 ns, 30-60 ns, 55-85 ns, and 80-110 ns, respectively. During the laser pulse there is a strong continuum with weak emission lines observed at the target surface. This continuum persists at the target surface only for a short time during the afterglow, then it subsides as the plasma moves away from the target. Again during the laser pulse as we look away from the target surface, the plasma becomes more optimally thin by evidence of strong line radiation. Immediately after the laser pulse has subsided there is an increase in source brightness. The source is again radiating as a strong continuum with weak lines. However, there is a dramatic difference in brightness distribution of lines that radiate during the laser pulse. As the plasma continues to move away from the target it becomes more optically thin; i.e., the continuum subsides with line radiation more evident.

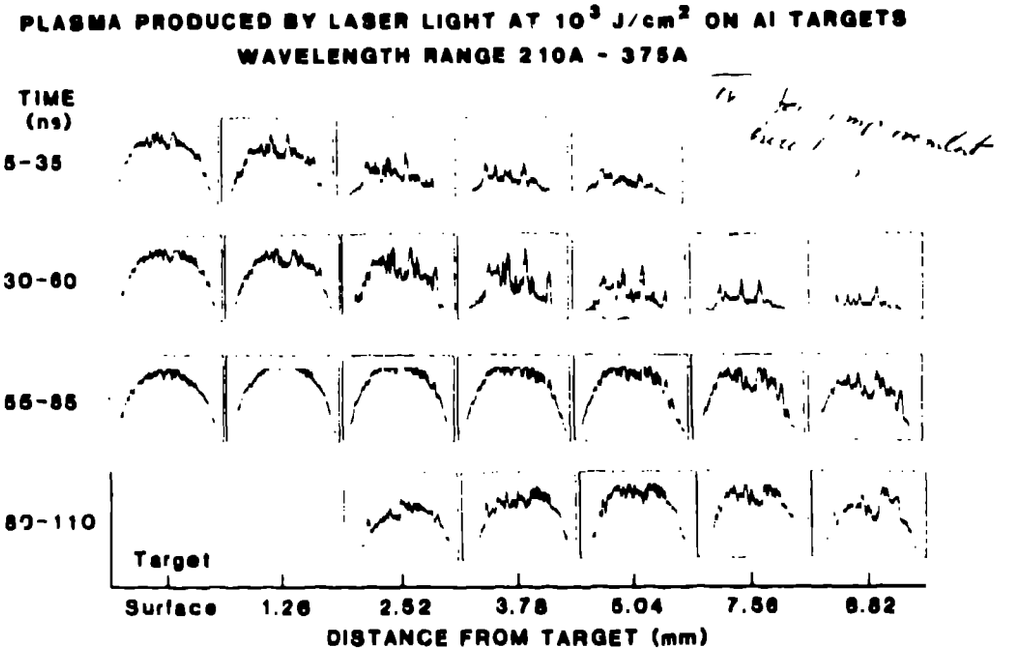

Figure 4. Spectral scans vs time and space.

As is apparent from the spectra shown, the intensity of the afterglow is considerably greater than the intensity of the plasma during the laser pulse. We further illustrate this in Fig. 5 where plasma brightness profiles at different times are compared. In Fig. 5, relative brightness, integrated over wavelength from 201 Å to 372 Å for four shots, at different times from t_o, were plotted against position from the target. The brightness of the plasma during the laser pulse (shots A & B) decay rapidly from the target surface. But after the laser pulse subsides the expanding the expanding plasma increases in brightness (shot C) and moves away from the target (shot D). The afterglow with a significantly larger radiating volume is much more intense than the plasma during the laser pulse.

We now analyze the line spectra during the time the laser pulse is on in an attempt to arrive at a plasma temperature. In Fig. 6 we show the aluminum spectrum from 30 to 60 ns after t_o at 3.2 mm from the target surface. We have identified several lines with transitions to ground states of Al VI (Al^{+5}), Al V (Al^{+4}) and Al IV (Al^{+3}). The Al IV line at 321 Å, in the spectrum, is probably the second order line of Al IV at 160 Å.

We will calculate the relative intensity of lines from different ionization states using a model which assumes local thermodynamics equilibrium (LTE). The calculated intensities of the observed Al VI 310 Å line and the Al V 280 Å line are shown in Fig. 7 plotted against temperature in eV for densities of $10^{18}/cm^3$, $10^{19}/cm^3$ and $10^{20}/cm^3$. We now take the ratio of brightness of the Al VI line @ 310 Å and the Al V line @ 280 Å from the spectrum in Fig. 6 and find the value for temperature that corresponds to that ratio for a given density from Fig. 7. The LTE model implies a temperature of 15 eV @ a density of $10^{19}/cm^3$ and 19 eV @ a density of $10^{20}/cm^3$. From ablation mass depth data we have reason to believe the density is near $10^{21}/cm^3$ for laser irradiance of 10^3 J/cm².[4]

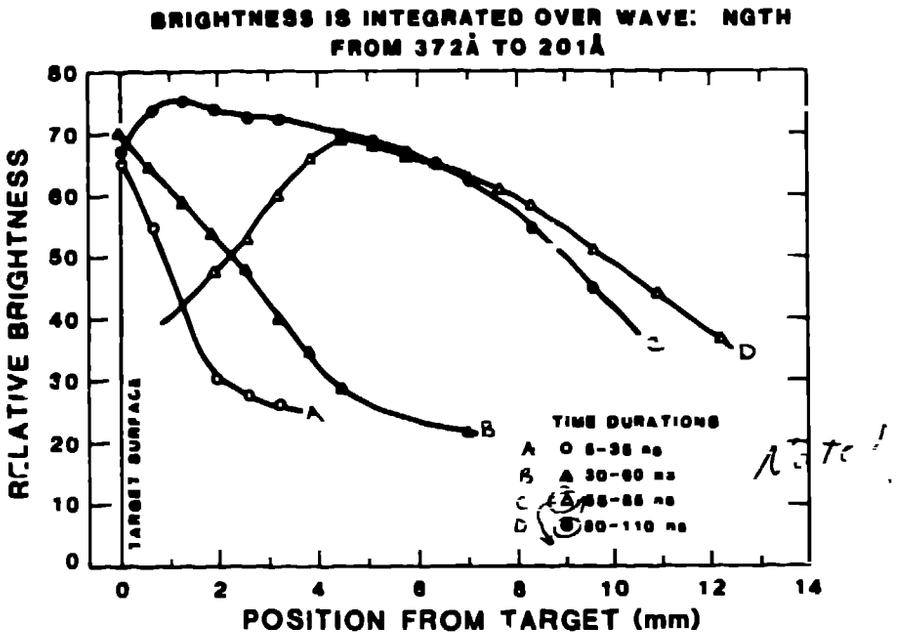

Figura 5. Plasma brightness profile as a function of time for aluminum targets.

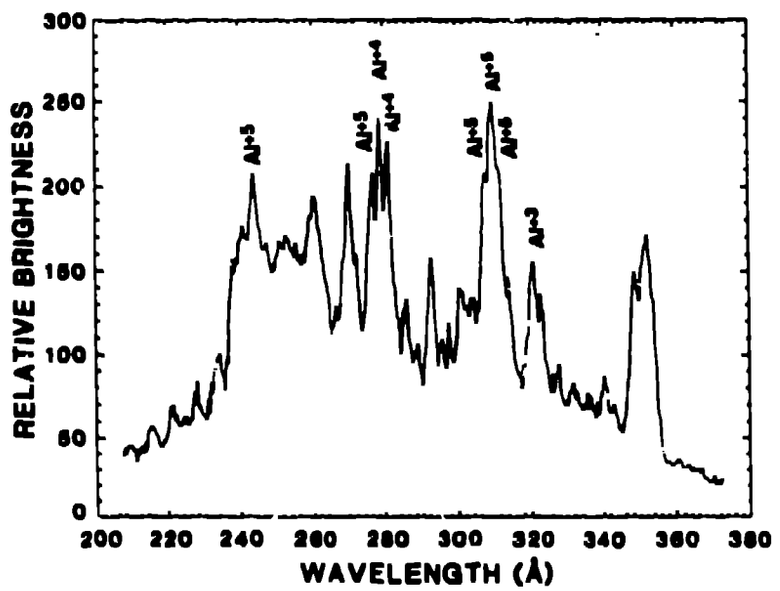

Figure 6. Spectrum of aluminum plasma during laser pulse 30-60 ns after laser t_o at 3.3 mm from target.

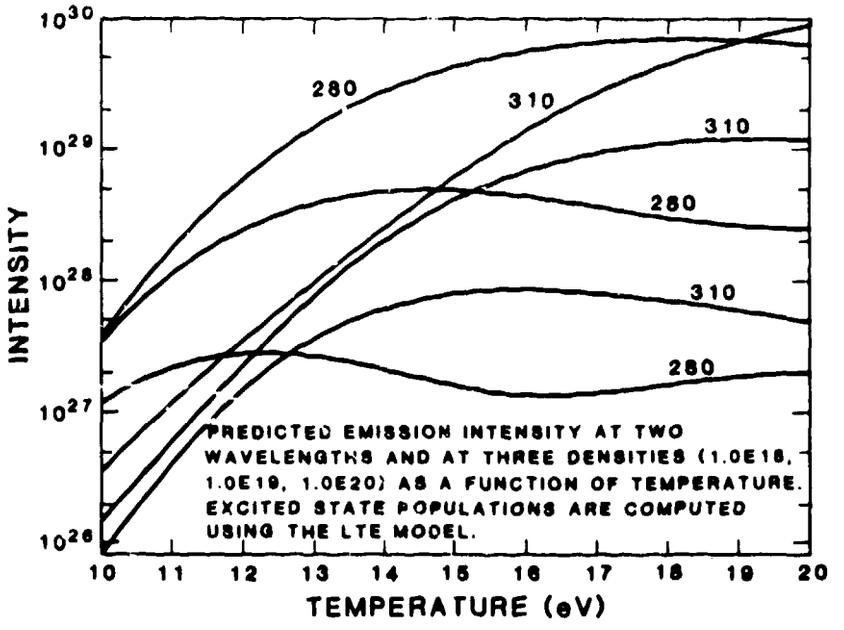

Figure 7. Predicted emission intensity at two wavelengths and at three densities (1.0 E 18, 1.0 E 19, 1.0 E 20) as a function of temperature. Excited State populations are computed using the LTE model.

In Fig. 8, we show a spectrum of the aluminum afterglow, 20 to 50 ns after the laser pulse has subsided, at 3.2 mm from the target surface. To date we have not been able to identify the lines in this spectrum. We need to examine the spectrum more closely for 2nd order contributions. The unidentified lines may be the result of combination.

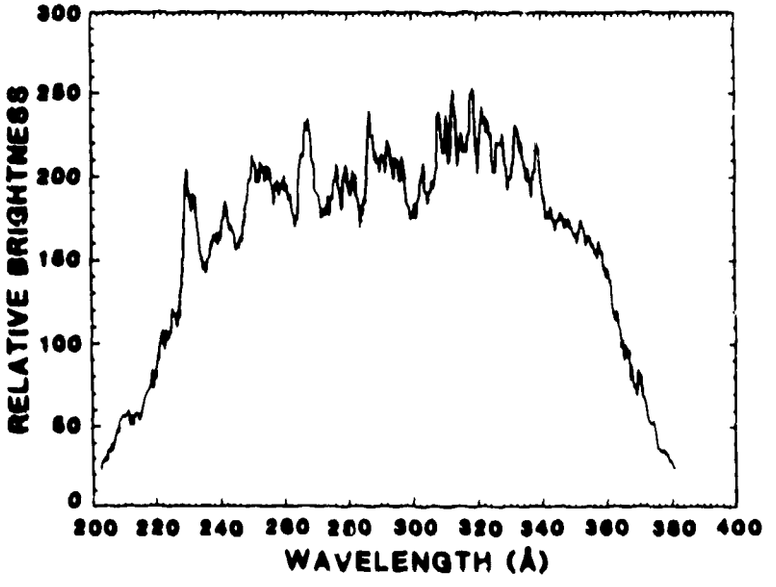

Figure 8. Spectrum of aluminum plasma 20-50 ns after laser pulse has zero amplitude at 3.2 mm from target.

Conclusions

Modeling of laser-target interactions requires verification by experimental measurements of plasma temperature and density. Spectroscopic measurements of excited state populations can be a powerful method to access the plasma temperature. The analysis of such data is subject to knowledge and conformation of atomic processes.

In the SPRITE experiments we observed spectral lines from excited states of Al IV, Al V and Al VI for laser irradiance of 10^3 J/cm^2. The modeled plasma temperatures, assuming LTE, reached a value between 15 eV and 19 eV. We observed strong emission after the laser pulse subsided, lasting about 50 ns. These emissions were several times the intensity of the plasma during the time of the laser pulse.

References

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3. Manufactured by Galileo Electro-Optics Corp., Galileo Park, Sturbridge, Massachusetts 01518.

4. R. S. Dingus, "Code Comparison for Optical-Laser Impulse Calculations," SUBWOG-GP Workshop, Los Alamos National Laboratory, Los Alamos, New Mexico, February 10-14, 1986.